

## REVIEW

# A review of soil and dust ingestion studies for children

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Soil and dust ingestion by children may be important pathways of exposure to environmental contaminants. Contaminated soil and dust may end up on children's hands and objects, because they play close to the ground. These contaminants can be ingested by children, because they have a tendency to place objects, including their fingers, in their mouths. Assessing exposure through this pathway requires information about the amount of soil and dust ingested by children. Estimates of soil and dust ingestion and information on the prevalence of the behavior have been published in the literature, but research in this area is generally limited. Three methodologies have been used to quantify soil and dust ingestion rates. In this paper, these are referred to as the tracer element method, the biokinetic model comparison method, and the activity pattern method. This paper discusses the information available on the prevalence of soil and dust ingestion behavior, summarizes the three methodologies for quantifying soil and dust ingestion, and discusses their limitations. Soil ingestion data derived from studies that use these methodologies are also summarized. Although they are based on different estimation approaches, the central tendency estimates of soil and dust ingestion derived from the three methodologies are generally comparable.

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## INTRODUCTION

Soil and dust ingestion can be important pathways of exposure to environmental agents, particularly for certain contaminants that tend to bind to soils (e.g., lead, dioxins, PCBs). Soil and dust can become contaminated as a result of direct or indirect discharges, atmospheric deposition of contaminants, runoff flow from contaminated areas, use of pesticides and fertilizers, and other processes. Outdoor soil and dust may be tracked into indoor environments becoming a source of indoor dust. Ingestion of soil and dust is a potentially important route of exposure to environmental contaminants for children, because they may spend a significant amount of time playing on the floor indoors, on the ground outdoors, and have a tendency to place objects, including their fingers, in their mouths. Soil and dust that has adhered to the hands and objects can be transferred to the mouth and inadvertently ingested. For example, the main pathway for lead exposure in young children is ingestion of indoor surface dust, as a result of the hand-to-mouth behavior.<sup>1–3</sup> Although some children ingest soil and dust unintentionally, others may engage in deliberative soil ingestion behaviors (i.e., soil pica).<sup>4</sup>

Estimating the potential dose of environmental contaminants from the ingestion of soil and dust is often a key component of human health risk assessments (e.g., Superfund), and provide the basis for cleanup of contaminated sites. Soil and dust ingestion rates are needed for estimating potential doses from soil and dust contaminants. However, research on quantifying and understanding soil and dust ingestion behavior among children is still somewhat limited, because it is resource intensive and presents challenges with the collection, analyses, and interpretation of the data. Several different methods have been used for collecting soil and dust ingestion data and these methods pose different types of uncertainties. Recently, the US Environmental Protection Agency (EPA) reviewed the various methods used for collecting

these data and provided recommended soil and dust ingestion rates in the *Exposure Factors Handbook: 2011 Edition*.<sup>5</sup> Soil and dust are defined as:

“Soil: Particles of unconsolidated mineral and/or organic matter from the earth's surface that are located outdoors or are used indoors to support plant growth. It includes particles that have settled onto outdoor objects and surfaces (outdoor settled dust).

Indoor settled dust: Particles in building interiors that have settled onto objects, surfaces, floors, and carpeting. These particles may include soil particles that have been tracked or blown into the indoor environment from outdoors as well as organic matter.

Outdoor settled dust: Particles that have settled onto outdoor objects and surfaces due to either wet or dry deposition. Note that it may not be possible to distinguish between soil and outdoor settled dust, as outdoor settled dust generally would be present on the uppermost surface layer of soil.”

“Soil” ingestion in this paper refers to the ingestion of both soil and outdoor settled dust, while “dust” ingestion refers to the ingestion of indoor settled dust only. Most of the currently available studies cannot accurately distinguish between soil and dust ingestion, but some researchers have attempted to estimate the relative contribution of outdoor soil to indoor dust using modeling<sup>6</sup> or element concentration ratios of soil to dust.<sup>7–9</sup> Dust ingestion may be an important exposure pathway for certain contaminants, especially for infants and toddlers who may spend more time indoors than older children.<sup>5,10</sup>

This paper provides a review of the current state-of-the-science on soil and dust ingestion. It summarizes the available literature on soil and dust ingestion (primarily for children). Although some limited soil ingestion data are also available for adults, the focus of

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this paper is on soil ingestion among children. This paper is not meant to validate or recommend one approach over another. Rather, it describes some of the limitations of the methodologies used to quantify ingestion rates and identifies areas where additional research may be helpful for refining soil ingestion estimates for certain age or other demographic groups.

## ESTIMATING THE PREVALENCE AND AMOUNT OF SOIL INTAKE

An extensive review of the literature on soil and dust ingestion behavior (publication years 1942–2012) was conducted. With the exception of a few of the more recent papers, these publications were used for establishing the recommendations found in EPA's *Exposure Factors Handbook: 2011 Edition*.<sup>5</sup> Many of the earlier studies were surveys that collected information on the prevalence of ingestion of soil and other materials but generally did not collect information about the amount of material ingested. Later studies used various approaches to assess soil and dust ingestion rates. Three methodologies were represented in the literature related to soil and dust ingestion rates. The first of these methodologies, the tracer element method, combines biomarker (i.e., tracer element) measurements in human feces and/or urine with measurements of the tracer element's presence in the environmental media (i.e., soil or dust). Some of the tracer element studies also provided evidence on the frequency of high soil ingestion episodes (i.e., soil pica). A second methodology, the biokinetic model comparison method, uses a biokinetic model to predict the quantity of soil ingested based on direct measurements of a biomarker in blood or urine for certain age groups of the population. The third methodology, the activity pattern method, combines information on activity patterns with assumptions regarding the transfer of soil and dust from the skin and objects into the mouth. All three methodologies have limitations for use in developing soil and dust intake rates.

### Prevalence Studies

Many of the early published studies on soil and dust ingestion were based on survey responses and were primarily used to quantify the prevalence of non-dietary ingestion. Some of these studies also provided information on the fraction of high soil ingesters in a population and the frequency of high soil ingestion episodes. Prevalence studies have been conducted at various locations throughout the United States<sup>4,11–17</sup> (see Table 1). Children's caretakers, or the children themselves (depending on their ages), were surveyed either in-person or by mail and asked about the frequency of mouthing behavior and ingestion of various non-food items. Questions about the amounts ingested were sometimes, but not always, included.

Survey response studies used to estimate the prevalence of soil and dust ingestion have certain limitations. In-person interviews may result in either positive or negative response bias due to distractions posed by young children, especially when interview respondents simultaneously care for young children and answer questions, while mailed questionnaires may allow participants to respond when they are not distracted. However, both formats may result in either positive or negative response bias for the following reasons: (1) respondents' perceptions of a "correct" answer and/or the desire to avoid negative emotions associated with giving a particular type of answer, (2) clarity of the questions posed, lack of understanding of definitions of terms used, and/or language and dialect differences between investigators and respondents, and (3) recall effects concerning past events.<sup>18,19</sup>

### Soil and Dust Ingestion Studies

Studies on soil and dust ingestion found in the literature can be categorized into three approaches: (1) the tracer element

methodology, (2) the biokinetic model comparison methodology, and (3) the activity pattern methodology.

**Tracer Element Methodology.** The tracer element methodology has been used to quantify the amounts of soil or dust ingested. Samples of soil and dust from children's residences and/or play areas, the children's feces, and sometimes urine are analyzed for the presence and quantity of tracer elements. It is assumed that these tracer elements are not metabolized into other substances in the body or absorbed from the gastrointestinal tract in significant quantities. Therefore, their presence in feces and urine can be used to estimate the quantity of soil and dust ingested by mouth. Several tracers have been used in this methodology, including: acid insoluble residue, aluminum (Al), cerium (Ce), lanthanum (La), neodymium (Nd), silicon (Si), titanium (Ti), yttrium (Y), and zirconium (Zr). Ideally, tracers used in this approach have low bioavailability, a high and homogenous concentration in soil, and low concentrations in food and medicines.<sup>20</sup>

Some researchers have corrected the estimates of soil and dust ingestion based on the amount of tracer present in foods and/or medicines consumed.<sup>9,21–24</sup> Other tracer element researchers have assumed a certain offset, or lag time, between ingestion of food, medication, and soil and dust and the resulting fecal and urinary output. Lag times used are typically assumed to be 24 h or 28 h.<sup>9,21,25</sup> Additionally, some researchers have accounted for time spent in various locations that could be expected to influence the relative proportion of soil and dust ingested (e.g., indoors, outdoors, away from home).

Soil and dust ingestion rates vary considerably depending on the tracer used for deriving the estimate. Some scientists hypothesized that the soil ingestion rate could not be higher than the lowest value obtained from the tracers used. This approach is known as the Limiting Tracer Method (LTM).<sup>26,27</sup> Because of the high degree of inter-tracer variability, others derived estimates based on the Best Tracer Methodology (BTM).<sup>22</sup> The BTM uses the ratios of food to soil tracer concentrations to correct for errors caused by transit time misalignments, ingestion of tracers from non-food sources, and non-soil sources.<sup>28</sup> A low food/soil ratio is desirable for this type of study. More recently, Stanek et al.<sup>29</sup> developed a stochastic model to evaluate the accuracy of soil ingestion estimates for various trace elements. Based on this analysis, Al, Si, and Zr were identified as the tracers with the least evidence of source error.<sup>29</sup>

The general equation used for estimating soil and dust ingestion by the tracer methodology is as follows:

$$T_{i,e} = (f_{i,e} \times F_i) / S_{i,e}$$

where:

$T_{i,e}$  = estimated soil or dust ingestion for child  $i$  based on element  $e$  (g/day),  $f_{i,e}$  = concentration of element  $e$  in fecal sample of child  $i$  (mg/g),  $F_i$  = fecal dry weight of child  $i$  (g/day), and  $S_{i,e}$  = concentration of element  $e$  in child  $i$ 's yard soil or dust (mg/g).

Additional terms are added to account for adjustments for tracer amounts in food, medicines, and so on. Table 2 summarizes the tracer methodology studies reviewed for estimating soil and dust ingestion.<sup>9,20–24,26–28,30–33</sup> Although not all researchers provided information about the shape of the distribution of soil and dust ingestion rates, some have found that these are skewed at the high end.<sup>20,34,35</sup>

There are several limitations and uncertainties associated with the tracer element studies shown in Table 2 such as: (1) study duration and location, (2) representativeness of soil tracer concentrations, (3) adjustment for non-soil tracer element concentrations, (4) gastrointestinal absorption and transit times, (5) fecal sample weights, and (6) sampling and analytical considerations. The tracer element studies shown in Table 2 were performed for short durations, for limited numbers of children, and conducted mostly

**Table 1.** Studies on the prevalence of ingesting soil, dust, or other non-food substances.

Reference	Location	Population	Results
Dickens and Ford <sup>11</sup>	Oktibbeha County, Mississippi	207 Rural black school children ( $\geq 4$ th grade)	52 Of the children ate dirt in the previous 10-16 days; clay was predominant type of soil eaten
Cooper <sup>12</sup>	Baltimore, Maryland	784 Children ( $\geq 7$ months) referred to a mental hygiene clinic	Parents/caretakers of 86 children responded positively to "Does your child have a habit, or did he ever have a habit, of eating dirt, plaster, ashes, etc.?"
Baltrop <sup>13</sup>	Boston, Massachusetts	439 Children (1-6 years)  277 Children (1-6 years)	19 Children ingested dirt (defined as yard dirt, house dust, plant-pot soil, pebbles, ashes, cigarette ash, glass fragments, lint, and hair combings) in the preceding 14 days. 39 children ingested dirt in the 14 days before the survey
Bruhn and Pangborn <sup>14</sup>	California	91 Mexican and "Anglo" low-income families of migrant agricultural workers	12 Of the 65 Mexican and 11 of the 26 "Anglo" respondents indicated consumption of "dirt" among their family members
Robischon <sup>15</sup>	Unspecified Location	130 Children (19-24 months) from urban well-child clinic	48 "Ate non-edibles more than once a week"; substances eaten by 30 of the children were: ashes (17), "earth" (5), dust (3), fuzz from rugs (2), clay (1), and pebbles/stones (1)
Vermeer and Frate <sup>16</sup>	Holmes County, Mississippi	50 Households (229 people; 140 children or adolescents)	Geophagy (regular consumption of clay over a period of weeks) in 16% of children < 13 years of age; average daily amount of clay consumed estimated at 50 g for both adults and children
Stanek et al. <sup>17</sup>	Western Massachusetts	528 Children (1-7 years) at well medical clinics	Daily mouthing or ingestion: 6% for sand and stones; 4% for soil and dirt; 1% for dust, lint, and dustballs. More than weekly mouthing or ingestion: 16% for sand and stones; 10% for soil and dirt; 3% for dust, lint, and dustballs. More than monthly mouthing or ingestion: 27% for sand and stones; 18% for soil and dirt; 6% for dust, lint, and dustballs
Gavrelis et al. <sup>4</sup>	United States nationwide	~21,000 Individuals (1-74 years)  ~25,000 Individuals, (0.5-74 years)	Prevalence of consuming non-food substances was 22.7% for the 1 to <3 year age group based on NHANES I (1971-75) and 12% based on NHANES II (1976-80). Prevalence estimates for the > 21 year age group was 0.7% and 0.4% for NHANES I (1971-75) and NHANES II (1976-80)

in northern regions. Therefore, they may not be entirely representative of children across all geographic regions, climates, and age ranges. The short-term duration of the studies makes it difficult to accurately derive long-term soil and dust ingestion rates. Most of these studies use the concentrations of tracer elements in composite soil samples collected from a child's yard and assume that these soils are representative of those ingested. This assumption may or may not be entirely accurate, and some researchers have attempted to address this limitation by collecting soil samples from daycare or community areas where children play. However, the homogeneity of the soils' tracer element content and its representativeness are potential factors that may bias soil ingestion estimates.

Some of the early tracer studies did not account for the contribution of tracer elements from non-soil substances (food, medications, and non-food sources, such as toothpaste) that children might swallow, but more recent tracer element studies have attempted to use a "mass balance" approach by adjusting for contributions from these non-food substances. However, none of the studies attempted to quantify amounts of tracer elements excreted in perspiration, tears, glandular secretions, or shed skin, hair, or fingernails and toenails, nor do they account for tracer element exposure via the dermal or inhalation routes, and thus they do not represent a complete mass balance methodology.

Accounting and correcting for the biases described above is one of the most difficult challenges when conducting analyses of soil and dust ingestion and interpreting their results. Stanek et al.<sup>20</sup> conducted a meta-analysis, including data from four soil and dust ingestion studies, aimed at predicting unbiased estimates of soil and dust ingestion. Their analysis resulted in soil and dust ingestion rates that are lower than other values

reported in the literature, but Stanek et al.<sup>20</sup> specifically excluded studies that targeted populations that were identified as having high soil mouthing behavior.

Despite these limitations, the tracer methodology has some advantages. The methodology can be used to indirectly measure soil ingestion and can be validated experimentally, and it allows for studying inter-individual variability.<sup>35</sup> However, implicit in the tracer element approach is the assumption that the tracers are not absorbed significantly in the gastrointestinal tract or metabolized or stored in the body and are therefore excreted.<sup>9,24,26,27,30</sup> Biases in the soil ingestion estimates would result if this assumption were incorrect for the tracer element used. In fact, some studies have shown the presence of tracer elements in urine samples, which is evidence that some absorption from the gastrointestinal tract has occurred.<sup>9,21,23,24</sup> According to Adriano,<sup>36</sup> dietary factors and the physiological condition of the receptor may affect the absorption of trace elements by the body. Differences in absorption based on age, nutritional needs, genetics, or other factors may have introduced some variability in the soil ingestion estimates derived from the soil tracer studies. Furthermore, the influence that soil properties may have on the uptake or excretion of tracers within the gastrointestinal tract is an area that has not been fully investigated. In addition, some studies in the literature suggest that lymph tissue structures in the gastrointestinal tract might serve as reservoirs for titanium dioxide in food additives and soil particles.<sup>37-39</sup> Entrapment within or releases from these reservoirs can affect estimates of soil and dust ingestion. There is also evidence that silicon has a role in bone formation,<sup>40</sup> suggesting a possible negative bias in the silicon-based soil ingestion estimates.

For studies that adjusted the soil ingestion estimates for non-soil (i.e., food and other non-dietary) sources of tracer elements in

**Table 2.** Soil ingestion studies using the tracer element methodology.

Reference	Location	Population	Tracers	Study design	Results
Binder et al. <sup>30</sup>	Helena, Montana	65 Children (1–3 years) living near lead smelter	Aluminum, silicon, titanium	Soiled diapers collected over 3-day period; composited samples of soil obtained from children's yards; excreta and soil samples analyzed for tracers	Arithmetic mean: 181 mg/day based on aluminum, 184 mg/day based on silicon, 1834 mg/day based on titanium, 108 mg/day based on minimum of the three individual tracer estimates for each child
Clausing et al. <sup>26</sup>	Netherlands	18 Children (2–4 years) attending nursery school; 6 hospitalized children (control group)	Aluminum, titanium, AIR	Fecal samples obtained over a 5-day period; soil samples from school; standard fecal dry weight of 10 g/day assumed	Arithmetic mean (without correcting for background tracer sources): 230 mg/day for aluminum, 129 mg/day for AIR, 1430 mg/day for titanium. Based on the LTM arithmetic mean: 105 mg/day; geometric mean: 90 mg/day. Average after correcting for background: 56 mg/day
Wong; <sup>31</sup> Calabrese and Stanek <sup>32</sup>	Jamaica	52 Children in government institutions (0.3–7.5 years and 1.8–14 years)	Silicon	Collected one fecal sample/month/child over 4 months; estimates corrected for dietary intake of tracer	For the older group, estimated to be 58 mg/day based on the mean minus one outlier; outlier was child with estimated average soil ingestion rate of 41 g/day over 4 months; for the younger group, mean estimated to be 470 mg/day. Of the 52 children studied, 6 had 1-day estimates of > 1000 mg/day
Calabrese et al. <sup>24</sup> , Barnes <sup>23</sup>	Amherst, Massachusetts	64 Children (1–3 years)	Aluminum, barium, manganese, silicon, titanium, vanadium, yttrium, zirconium	Duplicate samples of food, beverages, medicines, vitamins, excreta collected over 2-week period; soil/dust samples from children's homes/play areas; participants supplied with toothpaste, baby cornstarch, diaper rash cream, and soap with low levels of most tracer elements; fecal/urine samples collected	Mean ranged from – 294 mg/day based on manganese to 459 mg/day based on vanadium. Reanalyses of data: Calabrese et al. <sup>61</sup> reported average intake of 10–13 g/day for one child (for second study week); average: 6 g/day over 2 weeks. Calabrese and Stanek <sup>8</sup> estimated that 31.3% of indoor dust came from outdoor soil. Calabrese and Stanek <sup>25</sup> adjusted rates by correcting for positive/negative data biases; adjusted values: 97 mg/day based on yttrium to 208 mg/day based on titanium. Stanek and Calabrese <sup>62</sup> reanalyzed data assuming lag period of 28 h between food intake and fecal output; log-normal distribution model used to fit best estimate daily soil ingestion values based on the eight tracers; estimated median intake averaged over a year: 75 mg/day; 95th percentile: 1751 mg/day
Van Wijnen et al. <sup>27</sup>	Netherlands	292 Daycare children (1–5 years) in first sampling period; 187 children in second sampling period; 162 during both periods; 78 children at campgrounds	Aluminum, titanium, AIR	Estimates based on LTM; not corrected for dietary intake; average daily feces dry weight of 15 g assumed. Control group used to correct soil intake values	Geometric mean LTM: 111 mg/day (daycare children), 174 mg/day (campers). Arithmetic mean LTM: 162 mg/day (daycare children studied during both sampling periods); median: 114 mg/day. Corrected values: 69 mg/day (daycare children); 120 mg/day (campers); 90th percentile: up to 190 mg/day (daycare); up to 300 mg/day (campers); AIR was limiting tracer in about 80% of samples
Davis et al. <sup>9</sup>	3 City area in southeastern Washington	104 Children (2–7 years)	Aluminum, silicon, titanium	Collected soil/house dust and duplicate food, dietary supplements/medications, and mouthwash samples over 7 days; urine/feces collected over 4 days;	Mean soil ingestion: 39 mg/day for aluminum, 82 mg/day for silicon, 246 mg/day for titanium; median values: 25 mg/day for aluminum, 59 mg/day for silicon,

**Table 2.** (Continued).

Reference	Location	Population	Tracers	Study design	Results
				toothpaste with known tracer element content was supplied; information on dietary habits and demographics collected	81 mg/day for titanium. Mean soil/dust ingestion: 65 mg/day for aluminum, 160 mg/day for silicon, 268 mg/day for titanium; median: 52 mg/day for aluminum, 112 mg/day for silicon, 117 mg/day for titanium.
Stanek and Calabrese <sup>28</sup>	Combined results of Amherst, MA <sup>24</sup> and Washington State <sup>9</sup> studies	64 Children from Calabrese et al.; <sup>24</sup> 104 children from Davis et al. <sup>9</sup>	8 Tracers from Calabrese et al. <sup>24</sup> ; 3 tracers from Davis et al. <sup>9</sup>	BTM; used the lowest four food/soil ratios for each child, calculated on a per-week ("subject-week") basis	Mean: 104 mg/day; 95th percentile: 217 mg/day
Calabrese et al. <sup>22</sup>	Anaconda, Montana	64 Children (1–4 years) at a Superfund site	Aluminum, cerium, lanthanum, neodymium, silicon, titanium, yttrium, zirconium	Duplicate samples of meals/beverages, over-the-counter medicines/vitamins collected; feces collected over 7 days; soil and dust collected from the children's homes/play areas; toothpaste containing non-detectable tracer levels (except silica) provided; infants provided with baby cornstarch, diaper rash cream, and soap with low levels of tracers	Mean ranged from – 544 mg/day based on titanium to 270 mg/day based on neodymium; 95th percentile estimates ranged from 69 mg/day based on silicon to 1378 mg/day based on titanium. Calabrese et al. <sup>55</sup> quantified trace element concentrations in soil after sieving to particle size of <250 $\mu\text{m}$ in diameter; soil concentrations of three tracers (La, Ce, and Nd) were increased twofold to fourfold and soil ingestion estimates for these three tracers were decreased by approximately 60% compared with the results by Calabrese et al. <sup>22</sup> Stanek and Calabrese <sup>63</sup> reanalyzed the data, assuming a log-normal distribution; using "best linear unbiased predictors," the 95th percentile soil ingestion values over 7, 30, 90, and 365 days were estimated to be 133, 112, 108, and 106 mg/day, respectively. Stanek et al. <sup>35</sup> reported a long-term distribution with a mean of 31 mg/day and a 95th percentile of 91 mg/day
Calabrese et al. <sup>33</sup>	Western Massachusetts	12 Children aged 1–3 years observed to have frequent soil ingestion in the previous study	Aluminum, silicon, titanium	Mass balance tracer study with duplicate food sampling; both soil and dust samples collected	Mean soil estimates: 168 mg/day based on aluminum, 89 mg/day based on silicon, 448 mg/day based on titanium. Mean dust ingestion estimates: 260 mg/day based on aluminum, 297 mg/day based on silicon, 415 mg/day based on titanium. One child exhibited pica behavior
Davis and Mirick <sup>21</sup>	3 City area in southeastern Washington	Non-random subset of population in the study by Davis et al. <sup>9</sup> ; 12 children (3–7 years)	Aluminum, silicon, titanium	Duplicate samples of food/medications; feces collected for 11 consecutive days; urine samples collected; soil/house dust samples collected	Mean for all three tracers ranged from 37 mg/day to 207 mg/day; calculated by setting negative estimates to zero
Stanek et al. <sup>20</sup>	Meta-analysis of mass balance studies of soil ingestion in children	214 Children from Amherst, Anaconda, and Washington State studies	Aluminum, silicon	Used raw data from earlier studies to conduct meta-analysis; 11% of the subjects considered outliers and excluded	Mean (all ages combined): 26 mg/day; 95th percentile: 79 mg/day; mean by age: 4, 21, 32, and 41 mg/day, respectively, for ages 1 to <2, 2 to <3, 3 to <4, and 4 to <8 years. Excluding the children from the Anaconda site, mean and 95th percentiles were 43 mg/day and 90 mg/day, respectively

Abbreviations: AIR, acid insoluble residue; BTM, Best Tracer Method; LTM, Limiting Tracer Method.



the excreta, assumptions needed to be made regarding the gastrointestinal transit time, or lag time, between inputs (food, non-dietary non-soil, and soil) and outputs (fecal and urine). The gastrointestinal transit time assumption is a potential source of bias that some authors (e.g., Stanek and Calabrese<sup>28</sup>) called input/output misalignment or transit time error. Davis et al.<sup>9</sup> and Davis and Mirick<sup>21</sup> assumed a 24-h lag time in contrast to Calabrese et al.,<sup>24</sup> Barnes,<sup>23</sup> and Calabrese et al.<sup>22</sup> who assumed a 28-h lag time. Others have reported data from various sources and suggested an average lag time of 37 h for 1-year-old children and 5–15-year-old children.<sup>37</sup> Missing fecal or urine samples or incorrect fecal weights may be another source of error. Finally, inaccuracies inherent in environmental sampling and laboratory analytical techniques may result in uncertainties associated with soil ingestion estimates generated using this approach.

The “percentage of recovery” of different tracer elements was studied by Calabrese et al.<sup>22,24</sup> by having adults swallow gelatin capsules that contained known quantities of tracer elements in sterilized soil. It was shown that the percentage of recovery varies by tracer. For the tracers that displayed higher intertracer consistency, which included Al, Ce, Nd, Si, and Y, the percentage of recovery ranged from 77% to 150%.<sup>22</sup> Estimates based on a particular tracer element with a lower or higher recovery than the expected 100% would be biased in either a positive or negative direction.

**Biokinetic Model Comparison Methodology.** A second method described in the literature is the biokinetic model comparison methodology. This method compares direct measurements of a biomarker (e.g., blood or urine levels of a toxicant) with predictions from a biokinetic model that includes exposures to toxicants in air, food, water, soil, and dust via ingestion, inhalation, and dermal routes. This methodology reflects the general principle in aggregate exposure assessments in that it takes into account the concept that exposures from various pathways do not occur as independent events.<sup>41</sup>

An example of the use of this method would be to compare children’s measured blood lead levels with predictions from the Integrated Exposure and Uptake Biokinetic (IEUBK) Model using lead levels in the environmental media to which the children had been exposed as model inputs. The comparison of the model-predicted blood lead levels with actual blood lead levels can be used to confirm or refute the model’s input assumptions (e.g., soil intake rates). Based on the finding that the measured blood lead levels roughly match the biokinetic model predictions, the model’s default assumptions may be assumed to be roughly accurate for

estimating central tendency or typical intake for the assessed group of children. It should be noted, however, that such agreement between the predicted blood and actual blood lead levels would be a confirmation of the net impact of all model inputs and not just soil and dust intakes. The model’s default assumptions may not be as useful for predicting blood lead levels for highly exposed children. Table 3 summarizes the biokinetic model comparison studies reviewed for estimating soil and dust ingestion.<sup>42,43</sup>

This method can be used to estimate soil and dust ingestion rates that are representative of long-term environmental exposures over periods of up to several years and can also account for a range of seasons and climate conditions. However, the biokinetic model comparison methodology may contain sources of both positive and negative bias. For example, not accounting for all sources of contaminant to which children are exposed might result in the model under-predicting biomarker concentrations. Not accounting for all sources of contaminant could result in the false interpretation that the default exposure factors (e.g., soil ingestion rates) in the model are too high. This could result in inaccurate inferences about the model inputs. Another source of potential bias is the inherent model assumptions regarding the biokinetics of the biomarker being modeled. Positively or negatively biased predictions can also lead to incorrect inferences about the appropriateness of the exposure factors (e.g., soil ingestion rates) used in the model.

**Activity Pattern Methodology.** The third approach used to estimate soil ingestion is the activity pattern methodology. This method combines information on hand-to-mouth and object-to-mouth activities (e.g., microactivities) and time spent at various locations (e.g., microenvironments) with assumptions about transfer of soil to hands (e.g., soil-to-skin adherence) and from hands to mouth (e.g., saliva removal efficiency) and other exposure factors (e.g., frequency of hand washing) to derive estimates of soil ingestion. Microactivity information may be obtained using observational (e.g., videography) techniques or from survey responses. Table 4 summarizes the activity pattern methodology studies reviewed for estimating soil and dust ingestion.<sup>6,44–47</sup>

One of the advantages of this methodology is that it allows for the estimation of the separate contributions from soil and dust when using the modeling approach. In addition, the modeling approach provides information about variability and uncertainty in the soil and dust ingestion estimates.<sup>6</sup> The limitations and uncertainties associated with the activity pattern approach relate to the availability and quality of the underlying data used to

**Table 3.** Soil ingestion studies using the biokinetic model comparison methodology.

Reference	Location	Population studied	Study design	Results
Hogan et al. <sup>42</sup>	Historic lead smelting communities: Palmerton, PA; southeastern KS and southwestern MO; Madison, IL	478 Children with blood lead measurements and related soil and dust lead levels	Compared IEUBK-predicted blood lead levels with observed blood lead levels using observed house dust/soil lead levels, and default soil and dust intake rates, and other model parameters	Default IEUBK model dust and soil intake rates of approximately 50 mg/day soil and 60 mg/day dust averaged over children aged 1–6 years were roughly accurate in representing the central tendency intakes
von Lindern et al. <sup>43</sup>	Northern ID; site of community-wide soil remediation	Several hundred children (0–9 years)	Compared IEUBK-predicted blood lead levels with observed blood lead levels using observed house dust/soil lead levels, and default soil and dust intake rates, and other model parameters; developed statistical model that apportioned the contributions of community soils, yard soils of the residence, and house dust to lead intake	Used IEUBK default dust and soil intake rates; model over-predicted blood lead levels, with over-prediction decreasing as the community soil remediation progressed; results suggested that community soils contributed more (50%) than neighborhood soils (28%) or yard soils (22%) to soil found in house dust

**Table 4.** Soil ingestion studies using the activity pattern methodology.

Reference	Location	Population studied	Study design	Results
Lepow et al. <sup>44,45</sup>	Urban area of Connecticut	22 Children	Analyzed surface soil/dust samples from where children played, collected hand dirt on pre-weighed adhesive tape and measured the amount of soil and dust by weighing, and observed children's mouthing behavior during 3–6 h of normal play. Assumed that children put hands or other 'dirty' objects in their mouth 10 times a day and ingested 11 mg of soil each time	Estimated soil ingestion: 100 mg/day
Day et al. <sup>46</sup>	Manchester, England	Not applicable	Estimated the amount of soil that could adhere to a sticky sweet during 30 min of play and assumed that a child ate 2–20 sticky sweets per day; found that 5–50 mg of dirt stuck to a sticky sweet over that timeframe	Estimated soil ingestion: 10 to 1000 mg/day
Duggan and Williams <sup>47</sup>	London, England	Not applicable	Estimated that 2–7 mg of dust adhered to the forefinger and thumb; assumed that a child would put the finger and thumb in its mouth 10 times a day and ingest all of the dust	Estimated that dust ingestion would be about 20 mg/day
Özkaynak et al. <sup>6</sup>	Not applicable	Simulated population of children 3 to <6 years	Used US EPA's SHEDS-Multimedia model to estimate soil and dust ingestion rates using distributions of exposure factor values for hand-to-mouth activities; assumed soil and dust adhered to hands and remained until washed off or ingested by mouthing; object-to-mouth pathway for soil/dust ingestion was also addressed; outdoor matter was designated as "soil" and indoor matter as "dust"	Mean total soil and dust ingestion: 68 mg/day; approximately 60% originating from soil ingestion, 30% from dust on hands, and 10% from dust on objects; 95th percentile: 224 mg/day. The predicted soil and dust ingestion values fit a log-normal distribution

estimate soil ingestion rates. For example, microactivity data collected using videotaping or direct observation may be influenced by the presence of unfamiliar people.<sup>48–50</sup> Biases may also be introduced by misinterpretation or the inability of observers or videotapes to capture all mouthing behaviors. Collection of behavioral data via survey response questionnaires may also be biased as a result of misinterpretations of questions, recall/memory effects, and other factors. Additional uncertainties relate to the reliance on assumptions for important input parameters (e.g., surface areas of hands or objects that are mouthed, soil-to-skin adherence, saliva removal efficiency), some of which are chemical specific and may be difficult to accurately quantify.

## DISCUSSION OF LIMITATIONS

Table 5 shows the ranges of soil or soil and dust ingestion values obtained from the three methodologies used within various studies. Despite the differences in approaches used to derive soil ingestion rates and their limitations, the mid-point values in Table 5 are within the same order of magnitude across the three methodologies. However, there are several limitations and uncertainties that need to be considered when interpreting and using the soil ingestion values. The available data on soil and dust ingestion were derived from studies conducted primarily during the 1980s and early 1990s. Although children's behaviors, such as mouthing of hands and objects, may not have changed because they are part of normal development, activity patterns, micro-environments, or hygiene practices may be different. These may have an impact on the amount of soil and dust that is transferred to the mouth and ingested. Soil ingestion rates may also be influenced by geographic location, climate and season, and soil characteristics (e.g., silt or sand content). For example, extreme temperatures or precipitation events may limit the intake (e.g., during extreme cold or times when the ground is covered with snow would be expected to limit soil contact; extreme heat may

**Table 5.** Mean soil or soil and dust ingestion estimates from the three methodologies.

Methodology	Soil and dust ingestion (mg/day)
Tracer	26–470 <sup>a</sup>
Biokinetic	110
Activity pattern	10–1000 <sup>b</sup>

<sup>a</sup>Estimates based on data for Al and Si from Binder et al.<sup>30</sup>; Clausen et al.<sup>26</sup>; Wong<sup>31</sup>; Calabrese et al.<sup>24</sup>; Van Wijnen et al.<sup>27</sup>; Davis et al.<sup>9</sup>; Calabrese and Stanek<sup>32</sup>; Stanek and Calabrese<sup>28</sup>; Calabrese et al.<sup>22,33</sup>; Davis and Mirick<sup>21</sup>; and Stanek et al.<sup>20</sup> All are mean values except for Van Wijnen et al.<sup>27</sup> who used geometric mean of the LTM and Stanek and Calabrese<sup>28</sup> who used the BTM.

<sup>b</sup>Wide range of values based on rudimentary assumptions about soil ingestion activities in Day et al.<sup>46</sup>

also affect the time spent outdoors). Most of the tracer and biokinetic model comparison studies were conducted in northern latitudes where the weather would be expected to be moderate to colder than in southern geographic locations.

The temporal setting of the study (e.g., season) may also influence the estimated soil ingestion rates. Tracer element studies were conducted primarily during the summer and fall months, where children are expected to spend more time outdoors. Davis et al.<sup>9</sup> observed a consistent association between spending a greater number of hours outdoors and high soil ingestion levels. However, more time indoors can also increase exposure to indoor dusts. Studies have shown that the contributions from outdoor soils to indoor dust range from 8% to >80%, depending on various methodological approaches and study conditions.<sup>51</sup> In addition, hand-to-mouth and object-to-mouth frequencies have been found to be significantly greater indoors than outdoors.<sup>52,53</sup> Soil properties can influence the amount of soil that adheres to

**Table 6.** Recommended values for daily soil, dust, and soil + dust ingestion (mg/day) from EPA's *Exposure Factors Handbook: 2011 Edition*.

Age group	Soil <sup>a</sup>				Dust <sup>b</sup>		Soil + dust	
	High end							
	General population central tendency <sup>c</sup>	General population upper percentile <sup>d</sup>	Soil pica <sup>e</sup>	Geophagy <sup>f</sup>	General population central tendency <sup>g</sup>	General population upper percentile <sup>h</sup>	General population central tendency <sup>c</sup>	General population upper percentile <sup>h</sup>
6 Weeks to <1 year	30				30		60	
1 to <6 years	50		1000	50,000	60		100 <sup>i</sup>	
3 to <6 years		200				100		200
6 to <21 years	50		1000	50,000	60		100 <sup>i</sup>	
Adult	20 <sup>j</sup>			50,000	30 <sup>j</sup>		50	

Source: US EPA.<sup>5</sup><sup>a</sup>Includes soil and outdoor settled dust.<sup>b</sup>Includes indoor settled dust only.<sup>c</sup>Davis and Mirick<sup>21</sup>; Hogan et al.<sup>42</sup>; Davis et al.<sup>9</sup>; Van Wijnen et al.<sup>27</sup>; Calabrese and Stanek.<sup>25</sup> Central tendency values are intended to approximate the middle or center of the distribution.<sup>d</sup>Ozkaynak et al.<sup>6</sup>; Stanek and Calabrese<sup>28</sup>; 95th percentile value, rounded to one significant figure.<sup>e</sup>ATSDR<sup>56</sup>; Stanek et al.<sup>17</sup>; Calabrese et al.<sup>22,24,33,61</sup>; Calabrese and Stanek<sup>32</sup>; Barnes<sup>23</sup>; Wong<sup>31</sup>; Vermeer and Frate.<sup>16</sup><sup>f</sup>Vermeer and Frate.<sup>16</sup><sup>g</sup>Hogan et al.<sup>42</sup> Central tendency values are intended to approximate the middle or center of the distribution.<sup>h</sup>Ozkaynak et al.<sup>6</sup>; 95th percentile value, rounded to one significant figure.<sup>i</sup>Total soil and dust ingestion rate is 110 mg/day; rounded to one significant figure it is 100 mg/day.<sup>j</sup>Estimates of soil and dust were derived from the soil + dust and assuming 45% soil and 55% dust.

hands and may be ingested via hand-to-mouth contact. Driver et al.<sup>54</sup> found that the most important factor affecting adherence variability was particle size, followed by soil type and subtype. Experiments showed statistically significant increases in soil adherence to hands with decreasing particle size.<sup>54</sup> Tracer concentrations in soil can also vary with particle size. Calabrese et al.<sup>55</sup> found that the soil concentration of the tracers La, Ce, and Nd increased twofold to fourfold at the smaller soil particle size (i.e., <250  $\mu\text{m}$  vs 2 mm), while soil concentration did not change for Al, Si, Ti, Y, and Zr.

Demographic factors (e.g., age, gender, socioeconomic status) may also influence the rate of soil ingestion. Both males and females were represented roughly equally in the studies available in the literature. Most of the studies included children up to age 8 years, although a few included some children >8 years of age. Representativeness of socioeconomic status and racial/ethnic background was less consistent across studies. One study specifically targeted a predominantly rural black population,<sup>16</sup> whereas others focused on predominantly white populations of middle-to-high income or did not report this type of information about the study participants.

EPA's *Exposure Factors Handbook: 2011 Edition*,<sup>5</sup> provides recommended soil and dust ingestion values for use in human exposure and risk assessments. Soil and dust intake data generated from the three soil and dust ingestion methodologies described in this manuscript were considered while developing these recommendations. The estimated central tendency values are 60 mg/day for soil plus dust ingestion for children aged 6 weeks to <12 months, and 100 mg/day for children aged 1 year to <21 years; for soil only, these values are 30 mg/day and 50 mg/day, respectively (Table 6). "Central tendency" values are intended to approximate the middle or the center of the soil intake distribution and are used to represent typical or "average" ingestion. The upper percentile soil and dust ingestion recommendation for children 3 to <6 years of age is 200 mg/day (i.e., 95th percentile rounded to one significant figure). Upper percentile data for other age groups are limited, and recommendations were not provided

by the EPA. EPA's recommendations for upper percentile daily intake levels for children aged 1 to <21 years who are exhibiting soil pica behavior and geophagy are 1000 and 50,000 mg/day, respectively (Table 6).

The central tendency soil and dust intake values were based primarily on the biokinetic methodology analyses conducted by Hogan et al.<sup>42</sup> with the support of several studies in the literature, including: Van Wijnen et al.,<sup>27</sup> Davis et al.,<sup>9</sup> Calabrese and Stanek,<sup>25</sup> and Davis and Mirick.<sup>21</sup> The value of 85 mg/day from the IEUBK Model assumptions for children aged <1 year was adjusted downward by EPA based on the results from Hogan et al.<sup>42</sup> Hogan et al.<sup>42</sup> found an overprediction of blood lead levels, which translated into an overprediction of soil intake rates by a factor of 1.37. This results in a central tendency soil ingestion rate of 62 mg/day (i.e., 85 mg/day  $\times$  1/1.37). Hogan et al.<sup>42</sup> also showed that the default soil and dust intakes used in the IEUBK Model (i.e., approximately 50 mg/day soil and 60 mg/day dust for a total soil + dust intake of 110 mg/day) for children aged 1–6 years were roughly accurate in predicting blood lead levels for residential children in the locations studied. The average soil and dust ingestion rate of 100 mg/day (110 mg/day reduced to one significant figure) is within the range of values observed for the various tracer elements used in the tracer studies and is consistent with values reported using the LTM or BTM (see Table 2). These values are also similar to values estimated from activity patterns studies.

Data on soil pica behavior are limited. However, the studies reviewed suggest that some children exhibit soil pica behavior at least once during childhood. Studies have reported soil ingestion rates for these children ranging between 400 and 41,000 mg/day. The recommendation of 1000 mg/day is based on ATSDR's<sup>56</sup> definition of soil pica, and it falls within the range of values observed in the literature. Studies on human geophagy behavior have been limited to specific populations in specific areas where individuals acknowledge eating clays. The EPA recommendation for the amount of soil ingested by geophagy practitioners of 50,000 mg/day is based on the mean ingestion reported by Vermeer and Frate,<sup>16</sup> which is derived from a study population of



32 adults and 18 children. This value is also supported by four other studies; Geissler et al.,<sup>57</sup> which studied a group of children in Kenya, and Corbett et al.,<sup>58</sup> Rainville,<sup>59</sup> and Smulian et al.,<sup>60</sup> which provided clay consumption estimates for pregnant women. It is important to note that the EPA's recommendations for geophagy practitioners in the *Exposure Factors Handbook: 2011 Edition* may be more representative of acute exposures.

Despite similarities in results across the various methodologies, data gaps still exist. Not all demographic variables (e.g., age, sex, socioeconomic factors) and geographic locations are represented in the studies available in the literature. Longitudinal data needed to evaluate seasonal variability are also lacking. Interindividual variability cannot be fully characterized, because studies are conducted during the course of a few days. This information is important for identifying children who may have days where their soil and dust intake may be reaching pica levels. Except for the modeling approach used by Özkaynak et al.,<sup>6</sup> the current methodologies also do not allow for distinguishing the proportion of the ingestion that comes from soil *versus* dust. For certain contaminants or for some age groups, dust ingestion may be a more significant pathway than soil. More research in these areas is warranted.

## CONFLICT OF INTEREST

The authors declare no conflict of interest.

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